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2018

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## Publication Details

Libin Gong, Jan Nemcik and Ting Ren, Numerical Simulation of Unsaturated Infilled Joints in Shear, Proceedings of the 18th Coal Operators' Conference, Mining Engineering, University of Wollongong, 378-385.

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# NUMERICAL SIMULATION OF UNSATURATED INFILLED JOINTS IN SHEAR

Libin Gong<sup>1</sup>, Jan Nemcik, Ting Ren

**ABSTRACT:** Rock discontinuities filled with soil-like materials commonly exist in rock masses, where the infill material is usually unsaturated, and the joint could have a much higher shear strength compared with fully saturated conditions. Understanding the shear behavior of unsaturated infilled joints is important when assessing ground stability such as in open cut mines or underground excavations. However so far, research on this topic is rare and not mature. This paper investigates the shear behaviour of unsaturated infilled joints in the numerical software FLAC. The FLAC soil-water retention and permeability models were modified in *FISH* subroutine to consider infill porosity change. A series of constant water content direct shear tests on infilled joints under various ratios of infill thickness to asperity height ( $t/a$ ) were numerically conducted. Results highlight the necessity of correcting the intrinsic models in FLAC, and indicate that  $t/a$  ratio has a distinct influence on small-strain shear behaviour. Shear induced variations of fundamental infill parameters (e.g. matric suction, degree of saturation and saturated permeability) are discussed.

## INTRODUCTION

Infilled rock joints are one of the most important geological structures in practice (Brady and Brown 2013). When infilled joints are located in arid regions and above the ground water table, the infill material could remain relatively dry and unsaturated (Barton *et al.* 1974). This may occur not only in shallow ground, but also deep underground, as in some places the ground water table can be located several hundred meters from the surface. Even below the water table, the infilled joints inside the rock masses may still be unsaturated. For example, an unsaturated zone may be generated around the underground roadways, due to the action of desaturation caused by increased permeability in the broken ground (Matray *et al.* 2007). However, the infilled joints are usually assumed as fully saturated in engineering practice for safety and convenience. Compared with saturated condition, the unsaturated infilled joints could have much higher shear strength. Hence it is of importance to understand the shear behaviour of rock joints filled with unsaturated materials. However so far, research on this topic is rare and not mature. In the shear process, some fundamental hydraulic and mechanical parameters such as infill degree of saturation, matric suction and permeability, would vary with shear displacement. Understanding the variation trends of these parameters is important for proposing the stress-strain constitutive models of unsaturated infilled joints. As far as can be determined nobody so far has investigated the variation trends during shear. Indraratna *et al.* (2014) conducted a series of triaxial shear tests on unsaturated infilled joints under constant water content conditions. An empirical shear strength model was developed considering the influence of infill degree of saturation. However the changes of infill saturation and suction during shear were neglected. Later Khosravi *et al.* (2016) studied the shear behaviour of unsaturated infill joints in the laboratory; however the infill matric suction was kept constant during shear, and thus the supposed variation of suction was not considered.

In fact it is very difficult to monitor the variations of those parameters such as degree of saturation, matric suction, and permeability during shear in laboratory tests. The environment at the shear area can be extremely harsh. Even though some sensors can be installed inside the joint infill for example the high-capacity tensiometers to measure matric suction, satisfactory contact between the sensor and the infill material and possible damage of the sensors still provide some challenging problems. This paper tried to investigate the variation trends of those fundamental parameters during shear in a numerical way. The numerical software FLAC/Two-Phase flow model was adopted to simulate the direct shear tests of unsaturated infilled joints (Itasca Consulting Group 2011). The influence of  $t/a$  (infill thickness divided by joint asperity height) on the shear behaviour was investigated. Some practical implications based on the obtained results are discussed.

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## MODELLING PROCEDURES

This study modelled the 2D direct shear tests of unsaturated infilled joints in a laboratory scale using the software FLAC/Two-Phase flow model, under constant water content and constant normal load conditions. Simulated upper and lower rock parts of the joints were 20 mm high and 100 mm wide, respectively. Joints with a JRC value of 8-10 were modeled according to the Barton's standard joint profiles. The infill thickness varies from 1.74 mm to 7.35 mm, corresponding to specified  $t/a$  ratios ranging from 0.5 to 2.5. A total of five tests were conducted at different levels of  $t/a$ , a normal stress of 0.5 MPa, and initial infill degree of saturation of 50%. A grid of  $153 \times 30$  zones was built in the model. Model geometries with different  $t/a$  ratios are shown in Figure 1.

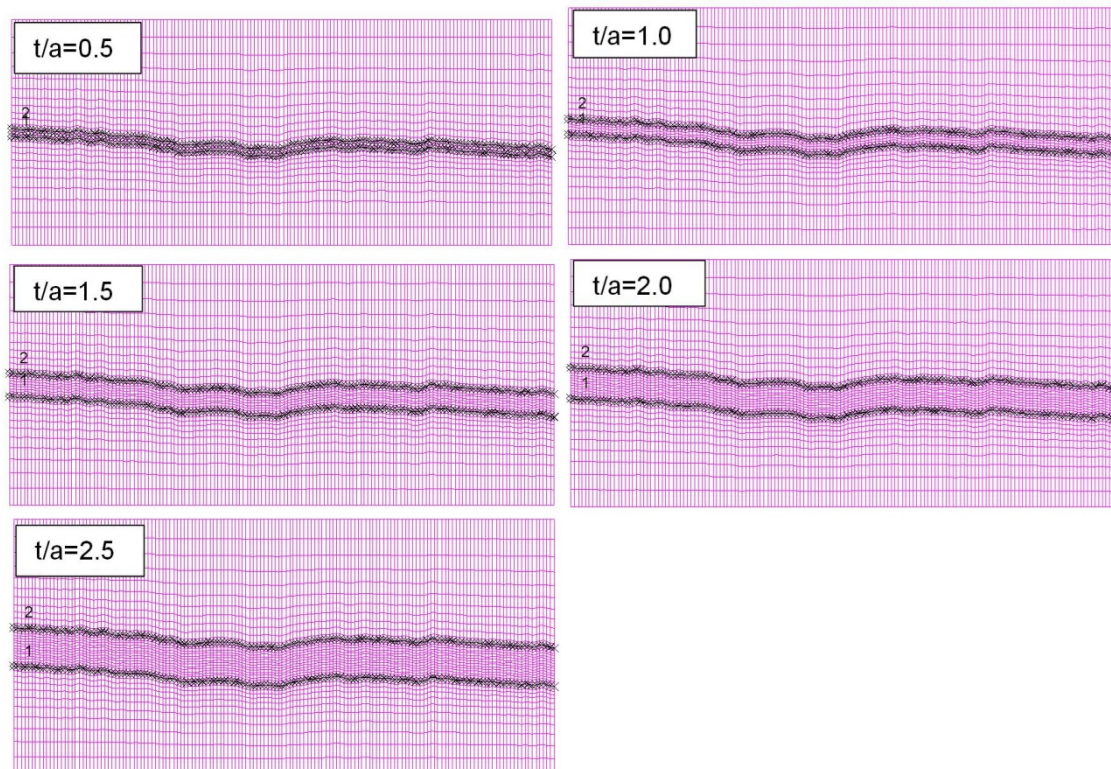


Figure 1: Grid and interface plots of initial models under different values of  $t/a$

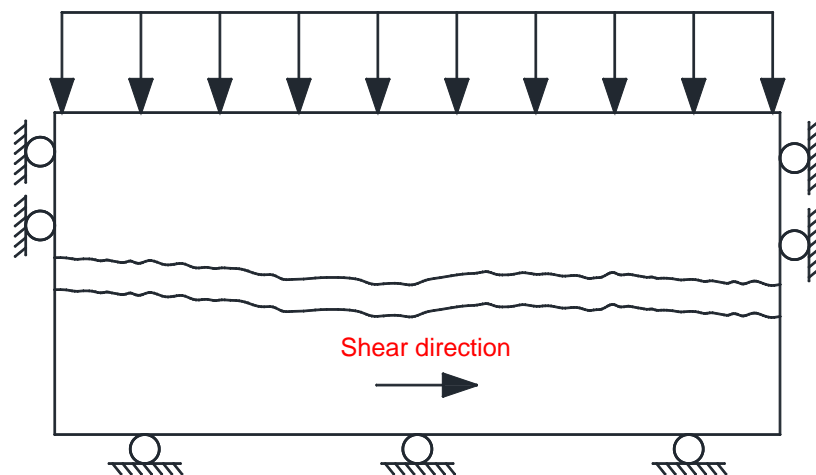


Figure 2: Boundary conditions of the model

Boundary conditions are plotted in Figure 2. Both sides of the upper block and the left side of the lower block were fixed in the x-direction; the bottom boundary was fixed in the y-direction. The boundaries of the infill material were impermeable to water. Pore air pressure was fixed as atmospheric in the system. After initial equilibrium, a horizontal velocity of  $1 \times 10^{-8}$  m/step was applied to the lower block to produce a shear displacement.

In this paper, only the small-displacement shear behaviour was investigated, due to the limitation of FLAC. Total shear displacement was 1.5 mm to prevent contact between joint asperities, and the upper and lower rock parts were isotropic elastic material. The infill layer was modelled as a Mohr-Coulomb material. Deformability and strength properties required in FLAC for both the rock part and the infill part are listed in Table 1. Permeability, water retention parameters and fluid properties are listed in Table 2. The rock-infill contacting planes were described using the unglued interface model in FLAC, where the Coulomb shear-strength criterion was applied to detect shear failure. Adopted interface properties are also listed in Table 1.

**Table 1: Infilled joint specimen properties required in FLAC**

Properties	Rock parts	Infill layer	Interfaces
Constitutive model	isotropic elastic	M-C model	
Dry density ( $\text{kg/m}^3$ )	2500	1500	
Elastic drained bulk modulus, $K$ (Pa)	$10.65 \times 10^9$	$7.8 \times 10^6$	
Elastic shear modulus, $G$ (Pa)	$4.36 \times 10^9$	$5.8 \times 10^6$	
Poisson's ratio	0.32	0.2	
Drained cohesion, $c$ (Pa)	-	$10 \times 10^3$	$10 \times 10^3$
Drained friction angle, $\phi$ ( $^\circ$ )	-	17	20
Dilation angle	-	0	
Tension limit (Pa)	-	0	
Initial porosity, $n_0$	0.544	0.544	
Shear stiffness, $k_n$ (Pa/m)			$3.1 \times 10^{10}$
Normal stiffness, $k_s$ (Pa/m)			$3.1 \times 10^{10}$

**Table 2: Permeability, water retention parameters and fluid properties**

Properties	Values
Initial saturated mobility coefficient ( $\text{m}^2/(\text{Pa}\cdot\text{s})$ )	$2 \times 10^{-15}$
Van Genuchten parameter, $a$	0.2275
Van Genuchten parameter, $b$	0.5
Van Genuchten parameter, $c$	0.5
Gallipoli parameter, $\phi$	0.004621
Gallipoli parameter, $\psi$	4.117
Fluid modulus for water, $K_w$ (Pa)	$2 \times 10^9$
Fluid modulus for air, $K_g$ (Pa)	1
Residual degree of water saturation, $S_{res}$	0
Undrained coefficient, $\beta$	1
Viscosity ratio, $\mu_w/\mu_g$	1

## POROSITY CONSIDERATION

In unsaturated soil mechanics, it is evident that porosity has significant influences on the Soil-Water Retention Curves (SWRCs) and permeability (Mašín 2010; Gallipoli, *et al.*, 2015; Hashem and Houston 2016; Carrier and Beckman 1984). However in FLAC/ Two-Phase flow model, these porosity dependencies are not accounted for automatically. To obtain more accurate simulation results, the intrinsic constitutive models were modified through *FISH* subroutines.

## Porosity calculation

As FLAC does not calculate the volume change induced porosity variation, the real porosity was first obtained in *FISH* functions.

In the Mohr-Coulomb model, elastic volumetric strain  $e^e$  is

$$e^e = \frac{\sigma_1 + \sigma_3}{\alpha_1 + \alpha_2} \quad (1)$$

where  $\sigma_1$  and  $\sigma_3$  are the major and minor principal stresses, respectively;  $\alpha_1 = K + 4G/3$  and  $\alpha_2 = K - 2G/3$ , where  $K$  is drained bulk modulus and  $G$  is shear modulus.

The volumetric strain in the large strain mode can then be approximated by

$$e_{\text{large}}^e = \frac{2e^e}{2+e^e} \quad (2)$$

The principal stresses in Eq. (1) are calculated by converting the Cartesian stress components available within *FISH*:

$$\sigma_1 = \frac{\sigma_{xx} + \sigma_{yy}}{2} + \frac{1}{2} \sqrt{(\sigma_{xx} - \sigma_{yy})^2 + 4(\sigma_{xy})^2} \quad (3)$$

$$\sigma_3 = \frac{\sigma_{xx} + \sigma_{yy}}{2} - \frac{1}{2} \sqrt{(\sigma_{xx} - \sigma_{yy})^2 + 4(\sigma_{xy})^2} \quad (4)$$

where  $\sigma_{xx}$ ,  $\sigma_{yy}$  and  $\sigma_{xy}$  are three components of stress tensor in the Cartesian coordinate frame.

The *FISH* variable  $e_{\text{plastic}}$  represents the accumulated plastic volumetric strain relating to the shear yield surface. Hence the total volumetric strain  $e_v$  is

$$e_v = e_{\text{large}}^e + e_{\text{plastic}} \quad (5)$$

Porosity  $n$  can then be approximated as

$$n = 1 - \frac{2-e_v}{2+e_v} (1 - n_0) \quad (6)$$

where  $n_0$  is the initial porosity of the material.

## Porosity-corrected SWRC

FLAC adopts the conventional van Genuchten SWRC model:

$$s = P_0 [S_e^{-1/a} - 1]^{1-a} \quad (7)$$

where  $P_0$  is a parameter relating to surface tension, intrinsic permeability and porosity of the material,  $S_e$  is the effective degree of water saturation, and  $s$  is matric suction of the porous material.

To consider porosity in Eq. (7), the residual degree of saturation and  $P_0$  are defined as:

$$S_{\text{res}} = 0 \quad (8)$$

$$P_0 = \frac{(1-n)^\psi}{\varphi \cdot n^\psi} \quad (9)$$

where  $\varphi$ ,  $\psi$  are constant parameters.

Equation (7) is then transformed to the Gallipoli SWRC model (Gallipoli et al. 2003):

$$s = \frac{(1-n)^\psi}{\varphi \cdot n^\psi} [S_r^{-1/a} - 1]^{1-a} \quad (10)$$

### Porosity-corrected permeability

Carrier and Beckman (1984) showed that porosity or void ratio of remolded clay has an influence on its saturated permeability:

$$k_s \approx 0.0174(1-n) \left\{ \frac{n-0.027(PL-0.242PI)(1-n)}{(1-n)PI} \right\}^{4.29} \quad (11)$$

where  $PI$  is plastic index for the material, and  $PL$  is plastic limit for the material.

As the laboratory infilled joint specimens were simulated in this study, and the infill material is considered as remolded clay, Eq. (11) was used in *FISH* subroutine to correlate saturated permeability with porosity.

### Unsaturated flow - mechanical coupling

In Two-Phase flow model, the unsaturated flow and mechanical calculation is coupled as shown in Figure 3.

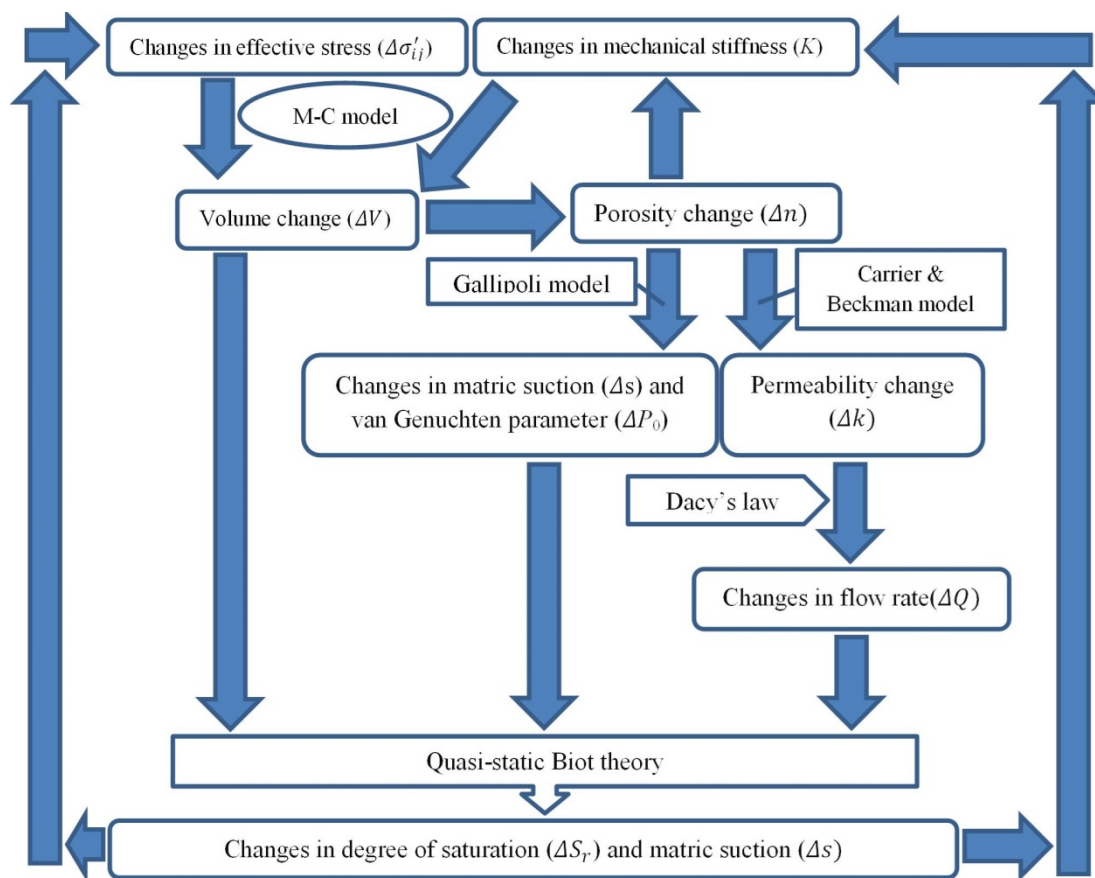


Figure 3: Two-phase flow – mechanical coupling in FLAC

## RESULTS AND DISCUSSION

### Porosity correction

As described above, porosity was considered in the SWRC model, saturated permeability and mechanical stiffness calculations. However it is too time-consuming to conduct the porosity correction at every calculation step. Hence this section investigates the influence of the number of porosity-update times, or the correction frequency during the whole shear process, on the infilled-joint shear behaviour. This number varies from zero (uncorrected for displacement of 1.5 mm), to 15 times (once per 0.1 mm shear displacement), to 30 times (once per 0.05 mm), and to 60 times (once per 0.025 mm).

All graphs in Figure. 4(a-f) clearly show that the porosity correction has a significant influence on the shear behaviour. After correction, a strain softening behaviour is clearly observed, matric suction decreases and the saturated permeability increases significantly, compared with the original case. Once corrected, the updating frequency has little effect on the shear stress curves. With increase of the frequency, dilation decreases, degree of saturation becomes larger, matric suction drops, and saturated permeability increases. Peak shear strength decreases with the increase of update frequency, and remains stable when the number is beyond 30. Therefore this value is adopted for the following simulation.

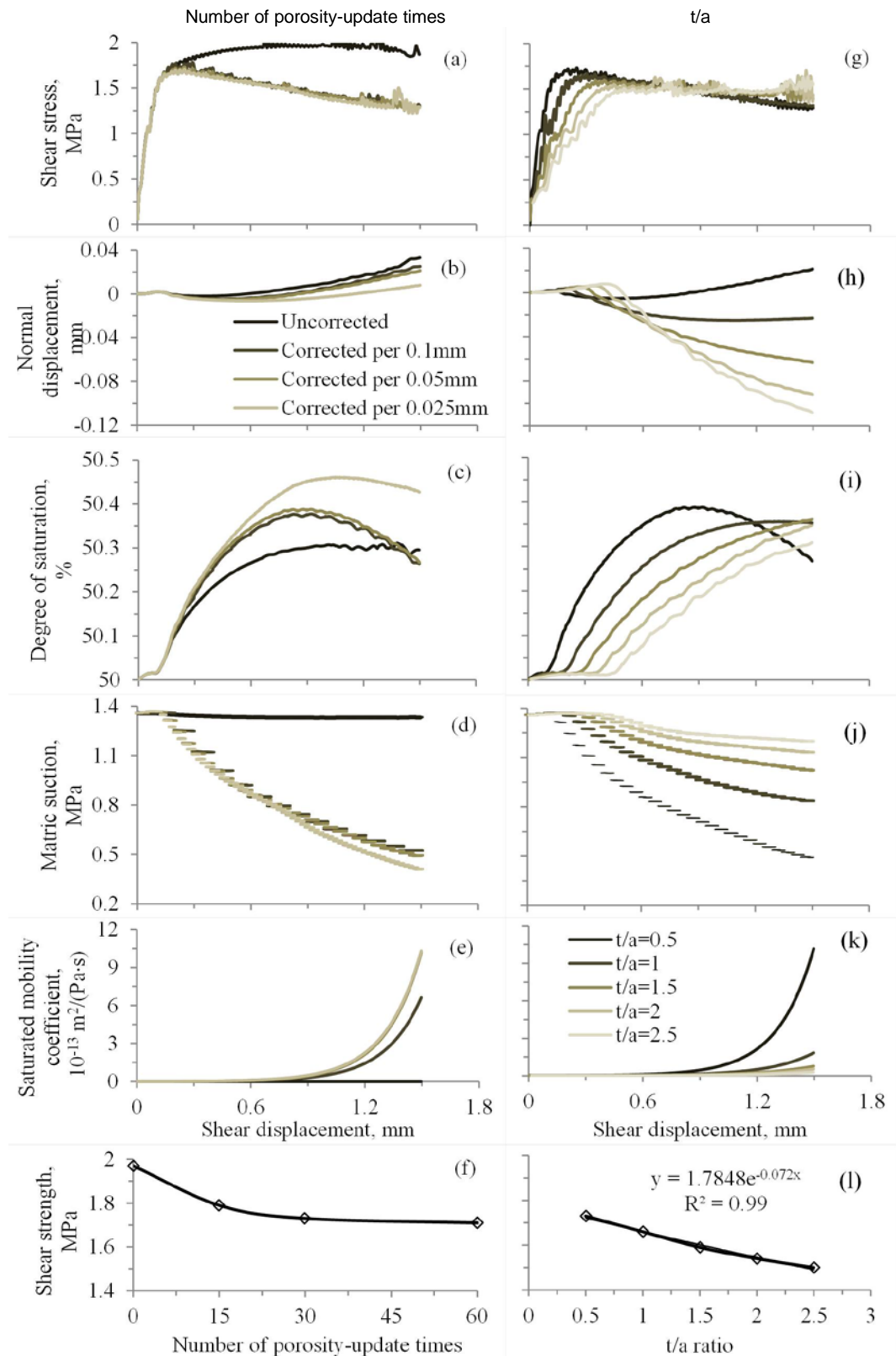
#### **$t/a$**

Tests under various  $t/a$  values (0.5, 1.0, 1.5, 2.0, 2.5) were then simulated and results are shown in Figure 4 (g-l). It is obvious that with the increase of  $t/a$  ratio, the strain softening behaviour diminishes, the infill is compressed more, the changes of degree of saturation, matric suction and saturated permeability all became gentler and peak shear strength decreases in an exponential form.

### **PRACTICAL IMPLICATIONS**

As discussed, study of the influence of porosity correction represents the inaccuracy of the FLAC intrinsic models. The residual shear strength may be overestimated considerably if the original FLAC models are used. This could cause an unsafe stability analysis for the jointed rock excavations in practice.

As this study focuses on the shear behaviour of infilled joints before joint asperities contact, Fig. 4(l) suggests that even the “soil peak” in the whole shear stress-shear displacement curve is sensitive to the  $t/a$  ratio. This is because with the increase of  $t/a$  ratio, the obstruction from the rough joint profile against the infill squeezing (flow) becomes weaker, and the maximum stress concentration factor within the infill layer decreases. This is important particularly in some circumstances where the infill layer is relatively large. Understanding the influences of  $t/a$  ratio on the “first stage” of the infilled joint shear may benefit the stability evaluation and reinforcement design.



**Figure 4: Shear behaviour of infilled joints under different porosity-update frequencies and  $t/a$  values**



## CONCLUSIONS

This paper employed the FLAC Two-Phase flow model to conduct a series of direct shear tests of unsaturated infilled joints under Constant Normal Load (CNL) and Constant Water content (CW) conditions. The following conclusions can be drawn:

1. Porosity correction in FLAC Two-Phase flow model is essential as the original constitutive models could overestimate the residual shear strength.
2. Generally during shear: stress increases to a peak and then decreases or remains stable; the infill layer contracts after an initial small dilation, followed by dilation or continued compression depending on the  $t/a$  ratio; degree of saturation increases and then remain steady or decreases; matric suction reduces with decaying slope especially after peak shear strength; saturated permeability increases significantly in the later stage exponentially.
3. With the increase of  $t/a$ : peak shear strength decreases exponentially; both the strain softening and dilation behaviour is less obvious; and the changes in degree of saturation, matric suction and saturated permeability all becomes smaller.

## ACKNOWLEDGEMENTS

The financial support provided by the China Scholarship Council [Grant No. 201406420027] and University of Wollongong for the first author is greatly appreciated.

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